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Electrophotographic Solid Freeform Fabrication

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14. ABSTRACT
Research at the University of Florida on Electrophotographic Freeform Fabrication is presented. In this fabrication technique, powder is picked up and deposited using a charged surface. Powder is deposited layer-by-layer to build parts. A test bed was designed and constructed to study this approach to solid freeform fabrication. Methods for charging and depositing powders using a photoconductor drum is being studied. Preliminary results obtained using this test bed are presented.

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Electrophotographic Solid Freeform Fabrication

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OBJECTIVE:

The objective of this research is to establish the feasibility of solid freeform fabrication of parts by electrophotographic powder deposition. Towards this end we are designing and building a prototype system or test facility that can deposit powder in the shape of the part cross-section layer by layer to build freeform solids. Various powders and powder characteristics that play an important role in controlling the accuracy and precision of the system are being studied.

APPROACH:

Electrophotographic Solid Freeform Fabrication is a novel powder based freeform fabrication technology that builds parts by depositing powders layer-by-layer using the electrophotography technique. In each layer two powders are used; one powder is of the material with which the part is to be made while the other powder provides support by holding the part powder in the required shape during subsequent compaction and sintering. The idea is illustrated in Figure 1. Powders of materials A and B are deposited as shown in a box-like container. Powder B acts as *support material* that surrounds powder A, the *part material.*

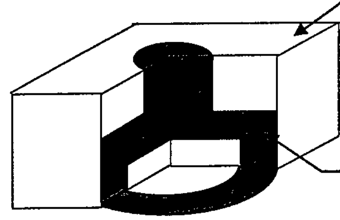

Figure 1. Powder based freeform fabrication

If material B has a relatively high melting point compared to material A, then upon compacting and sintering, powder A will fuse together and consolidate while material B will remain in powder form. The material B therefore serves as a die within which powder A is compacted and sintered. Since both powders are deposited layer by layer, the part and the "die" are being built simultaneously. The main challenge in implementing a rapid prototyping system based on this idea is to develop an automated method for accurately depositing the two powders in the desired shape. A powder deposition method based on electrophotography is described here, that will enable deposition of powder in layers with high accuracy. The feasibility of handling a variety of powders and the accuracy of powder deposition achievable by this method is currently being investigated.

There are many advantages to the proposed system over some of the currently available SFF systems. Due to the final compaction and sintering, relatively high density, strength and toughness should be achievable even for metal and alloy parts. Since the support material is in powder form, it is relatively easy to remove. In principle, this approach could be used to make parts of almost all materials that are readily available in powder form including, plastics, metals, ceramics, and alloys. Electrophotographic technology is a proven technology that has been successfully used in photocopying machines and printers. It is expected therefore, that focused research on various powders will enable precise and highly accurate deposition of a wide variety of powders.

A patent is pending for the process described here. The method is illustrated in Figure 2. A drum coated with photoconducting material is charged and the latent image is formed on it by projecting laser beam on its surface to selectively discharge regions on the surface of the drum. Two photoconducting drums, image developers, laser projectors etc are shown in the figure since we need to deposit two types of powders. The photoconducting drum on the right rolls in the clockwise direction and deposits powder A. The platform moves to the left when the powder A is being deposited. The image developer delivers charged powder to the close vicinity of the drum so that the powder jumps on to the charged regions of the drum. The powder deposited on the drum is then transferred on to the top layer of powder previously deposited on the build platform. To facilitate this transfer, a charging device is used to charge the top layer to the opposite polarity relative to the powder on the drum. The platform is moved such that there is no relative velocity between the platform and the surface of the rotating drum where it almost touches the top layer of powder or the platform. After the powder is deposited the platform passes under the heat roller, which heats and compresses the top layer of powder, to ensure that the part powder fuses (or at least acquires sufficient green strength).

When the platform moves to the right, the photoconductor on the left deposits support powder on to the top layer of powder on the build platform. This process is repeated to add the many layers of powders on the build platform. The back and forth motion of the platform needs to be controlled such that it is synchronized with the motion of the photoconductor drums.

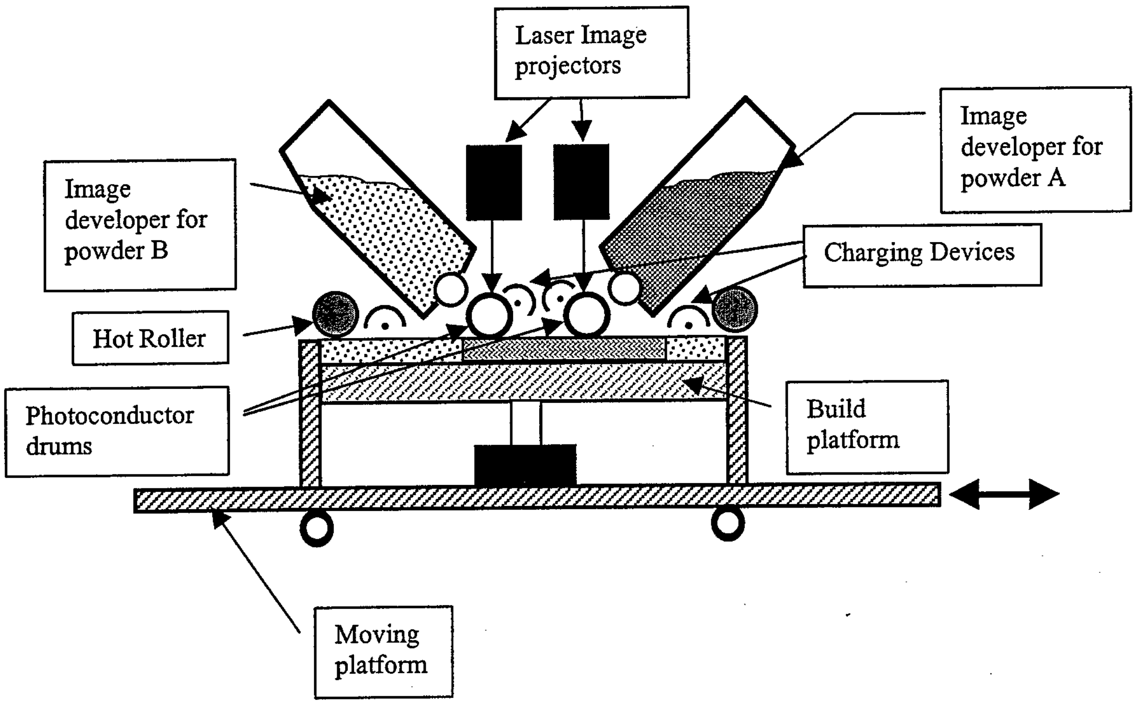

Figure 2. Photoconductor drum based embodiment

The image developing system (or image developer) serves two purposes. It electrostatically charges the powder to be deposited and also transports or delivers it to the vicinity of the latent image on the photoconductor. The charged particles then adhere to the latent image due to the electric field created by the charge on the photoreceptor, thus creating a real image on the photoconductor consisting of a uniform layer of powder deposited on the charged areas.

We are currently experimenting with various types of development systems to identify the system most suitable for our application. The most common approach for charging powder is to use a two component developing system, where "carrier" particles are mixed with the part or support powder that needs to be charged. These carrier particles are made of a magnetic material so that they can be transported using magnetic force. The carrier particles serve two purposes. Firstly, they induce electrostatic charge on the powder particles during mixing. Furthermore, the part / support powder particles, which are much smaller in size than the carrier particles, adhere to the carrier particle. Therefore, they get transported along with the carrier particles on magnetic rollers.

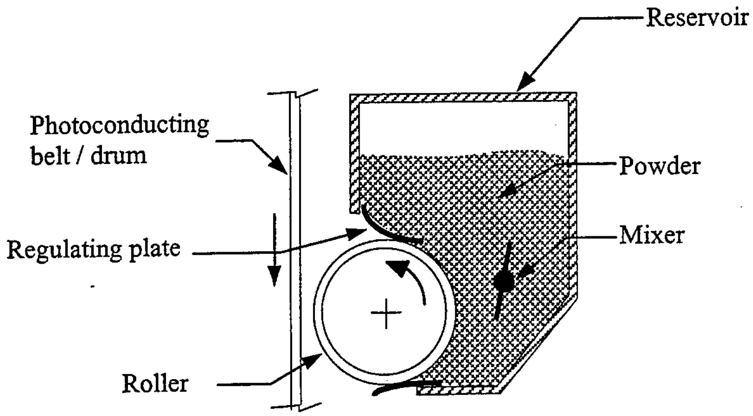

Figure 3. Image developer for depositing powder

Very fine powder can be used in this process so that each layer can be as little as 5-100 microns thick. This should lead to parts that have relatively good surface finish. Even though a large number of layers will be needed to make the part, the only data required for each layer is the cross-sectional image of the part. The application of electrophotography in photocopiers and printers clearly indicate the potential for fairly high-speed powder deposition. Furthermore, many of the components required for the proposed powder deposition technique are readily available. Photoconducting belts and drums are used in photocopiers and laser printers to pick up toner powder and deposit it on paper.

ACCOMPLISHMENTS (last 12 months):

The main accomplishments during the last 12 months may be summarized as:

a) Design, construction and preliminary testing of Test Bed-I that can deposit powder on a moving platform layer by layer.
b) Experimental study of the two-powder approach.
c) Application for Patent on the process.

a. Design and construction of Test Bed-I

A test bed was designed and constructed to test powder deposition using electrophotography for Solid Freeform Fabrication. The test bed consists of a movable build platform on which powder is deposited by a photoconductor drum. A design based on a photoconductive drum was preferred since it is more compact and less expensive than designs based on photoconductor belt. The photoconductor drum is charged using a charging roller, which is a contact charging device. The latent image is formed on the drum using an array of laser beams. The image developer used in the test bed consists of a container for holding powder and a magnetic roller that transports powder. A magnetized polymer toner powder was deposited layer by layer on to the platform. To transfer the powder on to the platform or the previous layers of powder, the top layer was charged using a charging roller. After the deposition of each layer, a heat roller was used to fuse the powder to the platform or previous layers. The test-bed is not yet fully automated and requires manual set up to print each layer. However, it serves as a useful facility to test layer by layer deposition of powder.

Currently, we are using an image development system in this test bed that uses a magnetic roller to transport powder to the latent image on the photoconductor drum. Furthermore, the powder is charged by applying an alternating electric field on the powder using two conducting electrodes. The system was designed to serve as a testbed to study the deposition of a variety of powders using electrophotography. Currently, due to the use of the magnetic roller in the image developer, either the powder has to be made of a magnetic material or a magnetic carrier powder has to be mixed with the powder. This is not a major concern since the magnetic carrier powder does not get deposited on the drum and platform. Also the developer is designed to charge a non-conducting powder. Alternate, designs for the image developer are being studied using this test bed.

Preliminary results indicate that the approach described here is capable of printing powder with precision consistent with electrophotography used in printing and photocopying applications. The test-bed is capable of achieving an accuracy of roughly 600 dots per inch. However, positioning subsequent layers precisely over previous layers will require robust control system, which is currently being designed.

b. Experimental Study of the two powder process

In order to identify powders suitable for use as part and support powder and to study the feasibility of obtaining high-density parts, we experimentally studied a combination of metal part powder and ceramic support powder. These powders were deposited as shown in figure 4 into a die. The powders were then compressed and sintered in a uniaxial hot press at a temperature lower than the sintering temperature of the support powder. The envelope of support powder distributes (albeit not uniformly) the uniaxial pressure in a manner similar to a hot isostatic press (HIP). After cooling, the sintered, fully dense part could be easily removed from the unsintered support powder envelope.

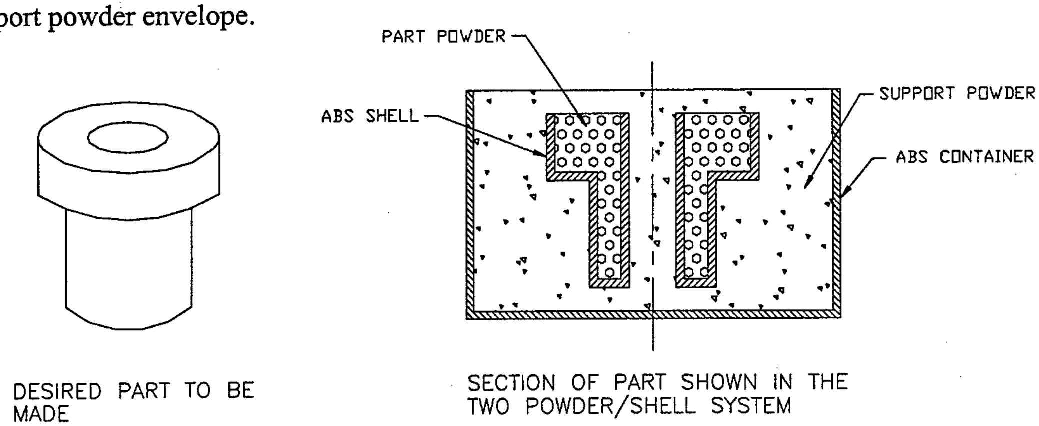

Figure 4: Two Powder-Polymer Shell System

In order to place part and support powder in the configuration shown in figure 4, a thin polymer shell (approx. 0.015") in the shape of the part to be manufactured was made using fused deposition modeling (FDM). The inside of the shell was filled with part powder and placed into a container such that the shell is surrounded by support powder.

The powder-shell system was then transferred to a uniaxial hot press where it was compressed and sintered. During the sintering stage, the polymer shell that contains the part powder is burned out and the support powder shifts to fill the void left by the shell. This requires that the support powder should flow readily under compressive stress. After the sintering and cooling process, the fully dense, consolidated part can be removed from the loose support powder.

Simple cylindrical shaped shell and container was used in our tests. The shell and container were created on a FDM 1650 rapid prototyping system. The powders were deposited manually. Copper powder of average size 45 microns (100 mesh), was used as the part powder. Titania and Alumina were tested as the support powder. Titania (TiO_2) powder used was approximately 0.25 microns while Alumina powder had an average size of 16 microns.

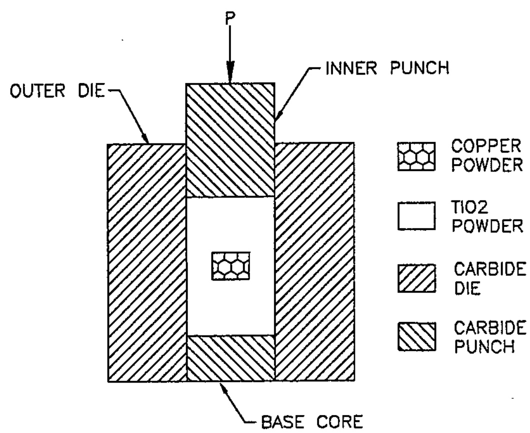

Figure 5: Schematic of Experimental Setup

The die in figure 5 has an inside diameter of 1-1/2" and the shell containing the copper powder was approximately 5/8" in diameter. The die/powder assembly was placed on a solid surface inside a uniaxial hot press. The press is capable of delivering the uniaxial load "P" while simultaneously heating the die using induction coils. A compressive load of 45 MPa was applied through the punch while the temperature of the die was held constant at 700 °C. The system was allowed to sinter for 20 minutes. During the sintering phase, the pressure on the die was maintained constant at 45 MPa. Subsequently, the die/powder system was allowed to cool for approximately three hours.

The compressed copper cylinder was removed and cut in half with a diamond saw. The cross section was then examined at 400X magnification. Although the inter-particle boundaries were slightly visible, the copper was approximately 97-99% dense. This positive result shows that the support powder did in fact transfer the applied load to the part powder effectively.

When titania powder was used as support powder, it did not stay as loose free-flowing powder. Upon examination under electron microscope, it was seen that the support powder had necked and partially sintered. This is due to the extremely small size of the TiO_2 powder (< 1 micron) that was used, coupled with the large applied pressure. The necking and partial sintering can be greatly reduced through the use of larger sized powder. When large size Alumina powder was used as support powder, it stayed in powder form and was easy to remove. Large, mono-sized spherical particles are less prone to mechanical locking due to their low packing factor. Spherical powder is also more fluid than irregular shaped powder due to the minimal contact area between adjacent particles. This will allow the support powder to more efficiently and uniformly distribute the applied load to the part powder. Lowering the sintering temperature will also help in decreasing chances of support powder consolidation.

While this preliminary study, definitely demonstrates the potential of the approach for fabricating high-density functional metal parts, it is obvious that much more research is needed to make this a viable process. Experimental studies are required to identify ideal temperature and pressure conditions for various powder combinations. It is also necessary to identify conditions that will ensure that the part powder undergoes uniform deformation during compaction. To manufacture dimensionally accurate parts, it is necessary to be able to predict deformations caused during compacting and sintering and scale the CAD model for the shell accordingly.

c. Patent Application

The University of Florida filed a provisional patent application in December 1997 for the processes described here. The Technology Licensing Office of the University of Florida conducted a market survey during Oct.-Dec. 1998 and found significant interest in the industry for the technology. Based on this a full patent application was filed by the University of Florida, December, 1998

SIGNIFICANCE OF THE RESEARCH

One of the major implications of the layer-by-layer manufacturing approach adopted by SFF systems is the promise and potential of these technologies to manufacture components and products that cannot be manufactured economically by any other means. Examples of these are very complicated part geometry (such as a block with internal cavities), components whose density or porosity varies within the part, components whose material composition and therefore properties varies within the part, components that have embedded technologies in them etc. Manufacturing functional components and unconventional designs mentioned above may well be the main future applications of SFF technologies.

The electrophotographic solid freeform fabrication described here has the potential to deliver on most of the above mentioned promises of SFF. The main advantages are listed below.

1. It is applicable to a wide range of materials.
2. The main components required for powder deposition are readily available and inexpensive due to its application in the multi-billion dollar printing and photocopying industry.
3. Using the two-powder approach, functional fully dense metal and alloy parts can be produced due to the final compaction and sintering.
4. Considerable energy savings can be achieved if parts are consolidated by compacting and sintering as compared to processes that need to melt the material for deposition or consolidation.
5. As in all powder-based approaches, no special support structures are required for overhanging features if support powder is used.
6. Relatively good surface quality can be achieved by using fine powder.

7. It is expected that in addition to traditional materials, a variety of composite materials such as metal matrix composites could be fabricated using this technology.
8. Future improvements to the powder deposition technique will allow mixing of powder in a controlled fashion to create composition gradients within the part to produce "gradient materials". It is possible to print in gray scales using electrophotography so that one could control composition precisely by printing two powders over each other in different gray-scales. This will allow composition variation within each layer as well as from layer to layer.
9. It should also be possible to embed electronics into parts by printing circuits (using appropriate conducting material) into parts using the same electrophotographic printing technology.

In the long run, these capabilities would remove many of the traditional manufacturing constraints and enable the manufacture of radical new products.

WORK PLAN (next 12 months):

The main tasks planned for the next 12 months are:

(i) A control system will be designed and implemented to enable automated operation of test bed-I to deposit multiple layers to build parts. Currently, we have acquired a 3-axes stand-alone controller that can be programmed using a PC to accomplish a variety of control tasks. We plan to use this controller to control the back and forth motion of the build platform as well as the up and down movements.

(ii) Test bed-I will be used to study the deposition of a variety of powders. Methods for charging and transporting different powders will be investigated.

(iii) Design of Test bed-II capable of depositing both part and support powders will be started after the initial experiments on test bed-I are completed. We hope to begin its design within the next 12 months and start construction in the following 12 months.

(iv) Software will be developed that can generate cross-sectional images from the CAD model of the parts to be manufactured. Initial work on this has already begun and we hope to have a working version within the next twelve to fifteen months.

PUBLICATIONS AND PATENT DISCLOSURES OR APPLICATIONS (last 12 months):

[1] Kumar, Ashok V., "Powder deposition and sintering for a two-powder approach to solid freeform fabrication", 9th *Solid Freeform Fabrication symposium*, 1998.

[2] Ashok V. Kumar and Hongxin Zhang, 1999, "Electrophotographic powder deposition for freeform fabrication", submitted for publication to the 10th *Solid Freeform Fabrication symposium*, 1999.

[3] Ashok V. Kumar and Aaron Wood, 1999, "Representation and design of heterogeneous components", submitted for publication to the 10th *Solid Freeform Fabrication symposium*, 1999.

[4] Kumar, A. V, 1997, "Method and Apparatus for Solid Freeform Fabrication Using Powder Deposition", Provisional Patent application, Docket number, UF-1786, filed by Law offices of Thomas Saitta, Jacksonville, FL.

[5] Kumar, A. V., 1998, Patent Application, "Solid Freeform Fabrication using powder deposition", application number 60/069,583, UF-1786, filed by Law offices of Thomas Saitta, Jacksonville, FL.